Constraining Antimatter Domains in the Early Universe with Big Bang Nucleosynthesis

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We consider the effect of a small-scale matter-antimatter domain structure on big bang nucleosynthesis and place upper limits on the amount of antimatter in the early universe. For small domains, which annihilate before nucleosynthesis, this limit comes from underproduction of ^{4}He. For larger domains, the limit comes from ^{3}He overproduction. Most of the ^{3}He from $\bar{p}^4$He annihilation is annihilated also. The main source of ^{3}He is photodisintegration of ^{4}He by the electromagnetic cascades initiated by the annihilation.

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If the early universe was homogeneous, antimatter annihilated during the first millisecond. However, baryogenesis could have been inhomogeneous, possibly resulting in a negative net baryon number density in some regions [1,2]. After local annihilation these regions would have only antimatter left, resulting in a matter-antimatter domain structure.

There are many proposed mechanisms for baryogenesis [1]. In models connected with inflation, there is no a priori constraint on the distance scale of the matter-antimatter domain structure that may be generated. If the distance scale is small, the antimatter domains would have annihilated in the early universe, and the presence of matter today indicates that originally there was less antimatter than matter.

We consider here such a scenario: a baryoasymmetric universe where the early universe contains a small amount of antimatter in the form of antimatter domains surrounded by matter. We are interested in the effect of antimatter on big bang nucleosynthesis (BBN) [3]. Much of the earlier work on antimatter and BBN [4–10] has focused on a baryon-antibaryon symmetric cosmology [5,6] or on homogeneous injection of antimatter through some decay process [8].

The smaller the size of the antimatter domains, the earlier they annihilate. Domains smaller than 100 m at 1 MeV, corresponding to 2×10^{-5} pc today, would annihilate well before nucleosynthesis and would leave no observable remnant.

The energy released in annihilation thermalizes with the ambient plasma and the background radiation, if the energy release occurs at $T > 1$ keV. If the annihilation occurs later, Compton scattering between heated electrons and the background photons transfers energy to the microwave background, but is not able to fully thermalize this energy. The lack of observed distortion in the cosmic microwave background (CMB) spectrum constrains the energy release occuring after $T = 1$ keV to below 6×10^{-5} of the CMB energy [11,12]. This leads to progressively stronger constraints on the amount of antimatter annihilating at later times, as the ratio of matter and CMB energy density is getting larger. Above $T \sim 0.1$ eV the baryonic matter energy density is smaller than the CMB energy density, so the limits on the antimatter fraction annihilating then are weaker than 6×10^{-5}.

For scales larger than 10 pc (or 10^{11} m at $T = 1$ keV) the tightest constraints on the amount of antimatter come from the CMB spectral distortion, and for even larger scales from the cosmic diffuse gamma spectrum [13].

We consider here intermediate domain sizes, where most of the annihilation occurs shortly before, during, or shortly after nucleosynthesis, at temperatures between 1 MeV and 10 eV. The strongest constraints on the amount of antimatter at these distance scales will come from BBN affected by the annihilation process.

Rehm and Jedamzik [9] considered annihilation immediately before nucleosynthesis, at temperatures T = 80 keV – 1 MeV. Because of the much faster diffusion of neutrons and antineutrons (as compared to protons and antiprotons) the annihilation reduces the net neutron number [4], leading to underproduction of ^{4}He. This sets a limit $R <$ few % to the amount of antimatter relative to matter in domains of size $r_A \sim 1$ cm at $T = 100$ GeV (4×10^6 m at $T = 1$ keV).

We extend these results to larger domain sizes, for which annihilation occurs during or after nucleosynthesis. Since our results for the small domains and early annihilation agree with Rehm and Jedamzik, we concentrate on the larger domains and later annihilation in the following discussion. Below, all distance scales given in meters will refer to comoving distance at $T = 1$ keV.

The case where annihilation occurs after nucleosynthesis was considered in Refs. [7]. Because annihilation of antiprotons on helium would produce D and ^{3}He they estimated that the observed abundances of these isotopes place an upper limit $R \lesssim 10^{-3}$ to the amount of antimatter annihilated after nucleosynthesis. As we explain below, the situation is actually more complicated.

Consider the evolution of an antimatter domain (of diameter $2r$) surrounded by a larger region of matter. At first matter and antimatter are in the form of nucleons

and antinucleons, after nucleosynthesis in the form of ions and anti-ions. Matter and antimatter will get mixed by diffusion and annihilated at the domain boundary. Thus there will be a narrow annihilation zone, with lower density, separating the matter and antimatter domains. At lower temperatures ($T < 30$ keV) the pressure gradient [14] drives matter and antimatter towards the annihilation zone. This flow is resisted by Thomson drag, which leads to diffusive flow [15].

Before nucleosynthesis, the mixing of matter and antimatter is due to (anti)neutron diffusion. When ^{4}He is formed, free neutrons disappear, and the annihilation practically ceases. If annihilation is not complete by then, it is delayed significantly because ion diffusion is much slower than neutron diffusion. There will then be a second burst of annihilation well after nucleosynthesis, at $T \sim 1$ keV or below. Indeed, depending on the size of the antimatter domains, most of the annihilation occurs either at $T > 80$ keV (for $r < 2 \times 10^7$ m) or at $T < 3$ keV (for $r > 2 \times 10^7$ m).

The annihilation is so rapid that the outcome is not sensitive to the annihilation cross sections. The exact yields of the annihilation reactions are more important. From the Low-Energy Antiproton Ring (LEAR) at CERN, we have data for antiprotons on helium, and also for some other reactions with antiprotons [16–18].

The annihilation of a nucleon and an antinucleon produces a number of pions, on average 5 with 3 of them charged [17]. The charged pions decay into muons and neutrinos, the muons into electrons and neutrinos. The neutral pions decay into two photons. About half of the annihilation energy, 1880 MeV, is carried away by the neutrinos, one third by the photons, and one sixth by electrons and positrons [4].

If the annihilation occurs in a nucleus, some of the pions may knock out other nucleons. Part of the annihilation energy will go into the kinetic energy of these particles and the recoil energy of the residual nucleus. Experimental data on the energy spectra of these emitted nucleons are well approximated by the formula Ce^{-E/E_0}, with average energy $E_0 \sim 70$ MeV, corresponding to a momentum of 350 MeV/c [17].

After ^{4}He synthesis, the most important annihilation reactions are $\bar{\mathrm{p}}$p and $\bar{\mathrm{p}}^4$He. According to Balestra *et al.* [18], a $\bar{\mathrm{p}}^4$He annihilation leaves behind a ^{3}H nucleus in 43.7 ± 3.2 % and a ^{3}He nucleus in 21.0 ± 0.9 % of the cases. The rms momentum of the residual ^{3}He was found to be 198 ± 9 MeV/c.

It is important to consider how these annihilation products are slowed down. If they escape far from the antimatter domain, they will survive; but if they are thermalized close to it they will soon be sucked into the annihilation zone [6].

Fast ions lose energy by Coulomb scattering on electrons and ions. If the velocity of the ion is greater than thermal electron velocities, the energy loss is mainly due to electrons. At lower energies the scattering on ions becomes more important. Below $T = 30$ keV, when the thermal electron-positron pairs have disappeared, the penetration distance of an ion of initial energy E depends on the ratio E/T [19]. For $E \gg (M_{\mathrm{ion}}/m_e)T$, the penetration distance is [20]

$$l = \frac{m_e}{M_{\mathrm{ion}}}\frac{E^2}{4\pi n_e (Z\alpha)^2\Lambda} \approx 2\times10^9 \frac{1}{AZ^2}\frac{1}{\eta_{10}}\frac{E^2}{T^3}, \qquad (1)$$

where $\Lambda \sim 15$ is the Coulomb logarithm, giving a comoving distance

$$l_{\mathrm{comoving}} \approx \frac{1}{AZ^2}\frac{1}{\eta_{10}}\left(\frac{E}{T}\right)^2 0.4\,\mathrm{m}. \qquad (2)$$

For smaller E/T, l keeps getting shorter, but not as fast as Eqs. (1) and (2) would give [19].

For ^{3}H and especially for ^{3}He, l would become comparable to the original size of the antimatter domain only well after the annihilation is over. Thus only a small fraction of these annihilation products escape annihilation. For D this fraction is larger, but still small, except for the largest domains considered here.

Neutrons scatter on ions, losing a substantial part of their energy in each collision. The neutrons from annihilation reactions have sufficient energy to disintegrate a ^{4}He nucleus. This hadrodestruction [21] of ^{4}He causes some additional ^{3}He and D production. Because protons are more abundant than ^{4}He nuclei, a neutron is more likely to scatter on a proton. The mean free path $\lambda = 1/(\sigma_{np} n_p)$ is larger than the distance scales considered here, so the annihilation neutrons are spread out evenly. At lower temperatures ($T \lesssim 1$ keV), neutrons decay into protons before thermalizing. At higher temperatures, the stopped neutrons form deuterium with protons.

The high-energy photons and electrons from pion decay initiate electromagnetic cascades [21–24]. Below $T = 30$ keV, the dominant processes are photon-photon pair production and inverse Compton scattering

$$\gamma + \gamma_{bb} \to e^+ + e^-, \quad e + \gamma_{bb} \to e' + \gamma', \qquad (3)$$

with the background photons γ_{bb}. The cascade photon energies E_γ fall rapidly until they are below the threshold for pair production, $E_\gamma \epsilon_\gamma = m_e^2$, where ϵ_γ is the energy of the background photon. Because of the large number of background photons, a significant number of them have energies $\gg T$, and the photon-photon pair production is the dominant energy loss mechanism for cascade photons down to [23]

$$E_{\mathrm{max}} = \frac{m_e^2}{22T}. \qquad (4)$$

When the energy of a γ falls below E_{max}, its mean free path increases and it is more likely to encounter an ion.

As the background temperature falls this threshold energy rises, and below $T \sim 5$ keV, $E_{\max}$ becomes larger than nuclear binding energies, and photodisintegration [21–24] becomes important. Photodisintegration of D begins when the temperature falls below 5.3 keV, photodisintegration of ^{3}He (^{3}H) below 2.2 keV (1.9 keV) and photodisintegration of ^{4}He below 0.6 keV.

Thus there are two regimes for photodisintegration: (1) between $T = 5.3$ keV and $T = 0.6$ keV, where the main effect is photodisintegration of D, ^{3}H, and ^{3}He; and (2) below $T = 0.6$ keV, where the main effect is production of these lighter isotopes from ^{4}He photodisintegration. Because of the much larger abundance of ^{4}He, even a small amount of annihilation during the second regime swamps the effects of the first regime, and only in the case that annihilation is already over by $T = 0.6$ keV, is D photodisintegration important [21–24]. Because of the difference in the neutron and proton diffusion rates, domains this small have already significant (neutron) annihilation before ^{4}He synthesis.

For the larger domain sizes, the most significant effect of antimatter domains on BBN turns out to be ^{3}He production from ^{4}He photodisintegration.

We have done numerical computations of nucleosynthesis with antimatter domains. Our inhomogeneous nucleosynthesis code includes nuclear reactions, diffusion, hydrodynamic expansion, annihilation, spreading of annihilation products, photodisintegration of ^{4}He and disintegration by fast neutrons [19]. Because of the lack of data on the yields of annihilation reactions between nuclei and antinuclei, we have not incorporated antinucleosynthesis in our code, but the antimatter is allowed to remain as antinucleons. This could affect our results at the 10% level.

For photodisintegration of ^{4}He we use the results of Protheroe *et al.* [24] scaled by the actual local ^{4}He abundance. The ^{3}He yield is an order of magnitude greater than the D yield [24]. The Protheroe *et al.* results assume a standard cascade spectrum. This will not be valid for temperatures below 100 eV, since $E_{\max}$ becomes comparable or greater than typical energies of the initial γ's from annihilation. It would be important to find out the true cascade spectrum for these low temperatures, since this will affect our results at the largest scales.

We have in mind a situation where antimatter domains of typical diameter $2r$ are separated by an average distance $2L$. This we represent with a spherically symmetric grid of radius L with antimatter at the center with radius r. For simplicity we assume equal homogeneous initial densities for both the matter and antimatter regions. This density is set so that the final average density after annihilation will correspond to a given baryon-to-photon ratio η. Since we are looking for upper limits to the amount of antimatter which come from a lower limit to the ^{4}He abundance and an upper limit to the ^{3}He abundance, we choose $\eta = 6 \times 10^{-10}$, near the upper end of the acceptable range in standard BBN, giving high ^{4}He and low ^{3}He.

We show the ^{3}He yield as a function of the antimatter domain radius r and the antimatter/matter ratio R in Fig. 1. For domains smaller than $r = 10^5$ m, annihilation happens before weak freeze-out, and has no effect on BBN. For domains between $r = 10^5$ m and $r = 10^7$ m, neutron annihilation before ^{4}He formation leads to a reduction in ^{4}He and ^{3}He yields. For domains larger than $r = 2 \times 10^7$ m, most of the annihilation happens after ^{4}He synthesis. Antiproton-helium annihilation then produces ^{3}He and D, but most of this is deposited close to the annihilation zone and is soon annihilated. The much more important effect is the photodisintegration of ^{4}He by the cascade photons, since it takes place everywhere in the matter region and thus the photodisintegration products survive. This leads to a large final ^{3}He and D yield. The same applies to n^{4}He reactions by fast neutrons from $\bar{\text{p}}^4$He annihilation, but the effect is much smaller, because $\bar{\text{p}}^4$He annihilation is less frequent than $\bar{\text{p}}$p annihilation, and a smaller part of the annihilation energy goes into neutrons than in the electromagnetic cascades.

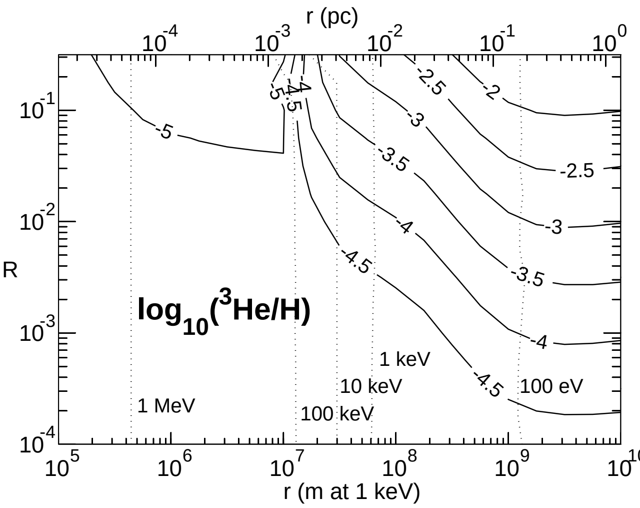

FIG. 1. The ^{3}He yield as a function of the antimatter/matter ratio R and the antimatter domain radius r. The distance scales are given both at $T = 1$ keV (in meters) and today (in parsecs). We plot contours of (the logarithm of) the number ratio ^{3}He/H. The dotted lines show contours of the "median annihilation temperature", i.e., the temperature of the universe when 50% of the antimatter has annihilated. Typically the annihilation is complete at a temperature lower than this by about a factor of 3.

We obtain upper limits to the amount of antimatter in the early universe by requiring that the primordial ^{4}He abundance Y_p must not be lower than $Y_p = 0.22$, and that the primordial ^{3}He abundance must not be higher than $^3\text{He/H} = 10^{-4.5}$ [3]. (The standard BBN results for $\eta = 6 \times 10^{-10}$ are $Y_p = 0.248$ and $^3\text{He/H} = 1.1 \times 10^{-5}$.)

For domain sizes $r \lesssim 10^{11}$ m (or 10 parsecs today), these limits are stronger than those from the CMB spectrum distortion. See Fig. 2.

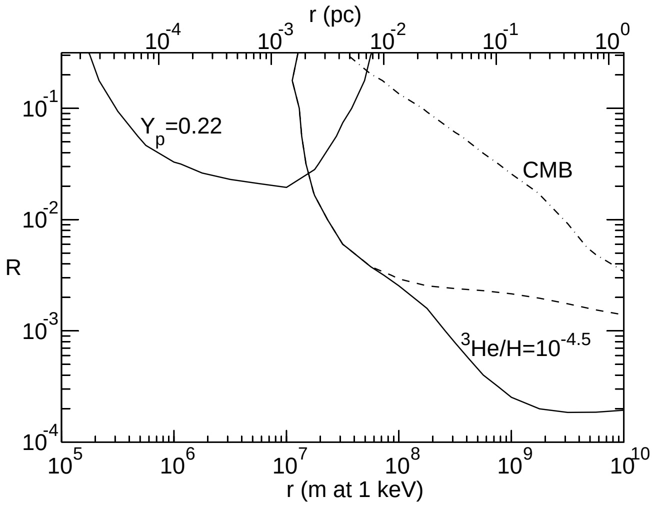

FIG. 2. Upper limits from BBN (solid lines) and CMB (dot-dashed line) to the antimatter/matter ratio R as a function of the antimatter domain radius r. The dashed line gives the upper limit from BBN if photodisintegration is ignored.

For $r < 10^5$ m, there is no BBN constraint on antimatter. For $r = 10^5$–10^7 m, the amount of antimatter can be at most a few per cent, to avoid ^{4}He underproduction. Our limit is somewhat weaker than that of Rehm and Jedamzik, since they considered a lower $\eta = 3.4 \times 10^{-10}$.

For larger domains, antimatter annihilation causes ^{3}He production from ^{4}He photodisintegration and the limit reaches $R = 2 \times 10^{-4}$ at $r \sim 10^9$ m.

There may exist small regions of parameter space where acceptable light element yields would be obtained for "nonstandard" values of η and large R [19]. Clearly the simultaneous reduction of ^{4}He and increase of ^{3}He and D suggest such a possibility for large η.

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